Efficient Methods for Time Synchronization in Distributed Radar Systems

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Abstract

Recently, the push to develop high-performance antenna arrays for space applications has underscored the economic and technical constraints associated with satellite missions. One cost-reducing strategy involves deploying a swarm of smaller, lighter satellites, though this approach introduces synchronization complexities. This paper evaluates two time synchronization techniques for distributed radar systems: the Two Way Time Transfer (TWTT) based Inter-Satellite Link (ISL) method and a Phase-Locked Loop (PLL) based method. The TWTT method utilizes Time Division Multiple Access (TDMA) for signal exchange among satellites, ensuring time alignment via delay filters. Conversely, the PLL method involves a primary satellite transmitting a reference signal to secondary satellites, which then recover the clock signal. Both techniques are analyzed for their implementation feasibility and effectiveness in maintaining synchronization, with simulation results demonstrating their potential in improving satellite communication performance.

Keywords

Time synchronization, distributed radar systems, satellite swarm, Two Way Time Transfer (TWTT), Inter-Satellite Link (ISL), Phase-Locked Loop (PLL).

1. Introduction

In recent years, a new technical trend has been spreading throughout the world. The objective is to develop increasingly high-performance antenna arrays for space applications from both a technological and an applicational point of view. The greatest economic impact of each mission is established by the weight of the launcher and the payload; therefore, implementation constraints are often also established to find the optimal compromise between weight and technology [1] used to perform the satellite or to improve its performance [2]. A possible solution to reduce satellite launch costs is to use a satellite swarm [3, 4] composed of many smaller and lighter satellites [5]. Although the implementation of these systems has the advantage of decreasing launch costs, they have the disadvantage of complexity of synchronization [6, 7, 8, 9, 10]. In this paper, two different synchronization techniques are analyzed. The first one is based on a direct Inter-Satellite link (ISL) using Two Way Time Transfer (TWTT), and the second is based on the transmission of a reference signal from a primary to one or multiple secondary that recover the clock with a PLL.

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2. TWTT Based ISL Link Method

The TWTT Based ISL Link is a Method used to reach the time synchronization between sensors in a multistatic system. The basic idea is to broadcast signal flight times and offset delays among various local oscillators information between nodes and exploit this information to align the flow of transmitted or received data with true delay filters. The ISL is performed using a Time Division Multiple Access (TDMA) method: to each node is assigned the time intervals to listen to and transmit data within the formationas as reported in [11] and [12], for which the implemented software has been refactored accordingly [13]. In order to carry out the TDMA technique and to ensure that the time intervals will be respected, all nodes must first achieve coarse synchronization. This can be achieved by using a highly stable frequency source and GPS pulse-per-second (PPS) tamed crystal oscillator.
To achieve fine synchronization, the i-th node must first broadcast a chirp signal, denoted as $s_i(\tau_i)$, which is modulated on a carrier of frequency f_c and phase γ_i^{tx}:

$$w_i(\tau_i) = s_i(\tau_i) \cdot e^{-j2\pi f_c(\tau_i)} \cdot e^{j\gamma_i^{tx}}$$

We can represent the signal received by the j-th sensor at a certain distance and sampled at f_s as:

$$r_{i,j}[n] = s_j\left[n - f_s\left(\varphi_i - \varphi_j + \frac{R_{i,j}}{c}\right)\right] e^{-j2\pi f_c\left(\varphi_i - \varphi_j + \frac{R_{i,j}}{c}\right)} e^{j\gamma_{i,j}^{\text{err}}}$$

To compute the time of arrival (and thus the delay time) during reception, it is necessary to perform the following correlation:

$$d_{i,j}(\tau_i) = r_{i,j}(\tau_i) * s_j^*(-\tau_i)$$

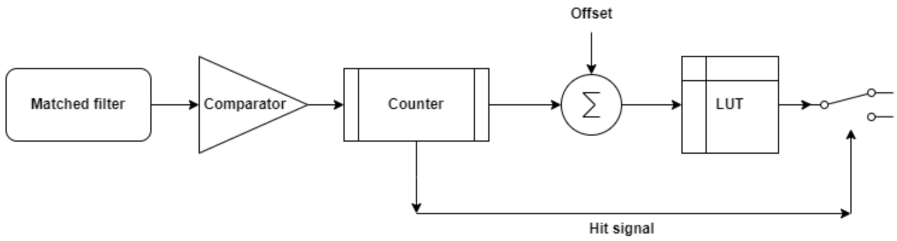

Figure 1: Simulink block diagram of sensor Rx section.

The maximum of this convolution correspond to the delay value associated with the clock temporal delays and the time of flight (TOF).

$$t_{pk:i,j} = argmax_{\tau_i}|d_{i,j}(\tau_i)|$$
$$= \varphi_i - \varphi_j + TOF_{i,j}$$

Once the time corresponding to the peak of the correlation has been found, the sample corresponding to this time can be determined using the sampling frequency f_s:

$$n_{pk:i,j} = f_s \cdot t_{pk_i,j}$$

2.1. Simulation model

The core issue is not the implementation of BPSK or QPSK encoding, but the conversion of arrival times into information suitable for use as a modulating signal for transmission. The chosen method involves converting these temporal values into voltage levels, which could be utilized with an encoder before transmission.

The proposed Rx architecture is shown in Fig. 1. Following the correlation using the matched filter, there is a comparison process aimed at resetting a set/reset counter in free-counting mode. The counter continues to count indefinitely until reset by an external signal corresponding to the correlation peak. The conversion to amplitude was achieved by implementing a memory that contains various delay values in terms of samples. This memory is scanned by the previously introduced counter, and through the "hit" signal generated by the counter itself, it becomes possible to sample the time value as amplitude. While in Simulink the transmission and reception process was simulated, in Matlab the iterative true peak detection algorithm was employed. This iterative process generates $\hat{\varphi}_i$ at each step, which will be applied to different chirps before transmission. The goal is to achieve perfect synchronization by aligning all signals ideally; where:

$$\hat{\varphi}_i = \frac{1}{N}\sum_j \hat{\Phi}_{i,j}$$

In this study, the classic Quadratic Least Squares method was used because it was found to have acceptable performance as shown in [14]:

$$\tilde{n}_{pk} = n_{pk} - \frac{y_2 - y_0}{2y_0 - 4y_1 + 2y_2}$$

2.2. Simulation results

During the simulation, the correlation peaks initially appear separated because the average value of the pre-transmission shift has not yet been processed. These peak separations indicate the delay of different transmission epochs (Fig. 3). This delay prevents synchronous transmission, making the system unusable. Subsequently, synchronization epochs will be performed to observe how the peaks' distances converge, as shown in Fig. 2.2. This algorithm is continuously iterated so that the chirps overlap as much as possible. Only in this way can we compensate for delays caused by temporal clock drifts among the various nodes.

In Fig. 2, the iteration of the algorithm throughout the entire working period is shown; it is clear that it is possible to correct a few tenths of a sample.

3. PLL Based ISL Method

The second method analyzed is an implementation of a PLL based architecture [15, 16, 17]. This architecture has a primary sensor and n secondary sensors; each secondary sensor receives a wave from the primary and synchronizes its clock on it. When all clocks are synchronized each node will be in phase depending on the distance from the primary sensor [18, 19].

3.1. Simulation model

The simulated PLL transfer function, responsible for engaging the phase of the signal transmitted by the primary sensor, is:

$$G_0(s) = 5.78\frac{1 + s8.1 \cdot 10^-3}{s^2}10^7$$

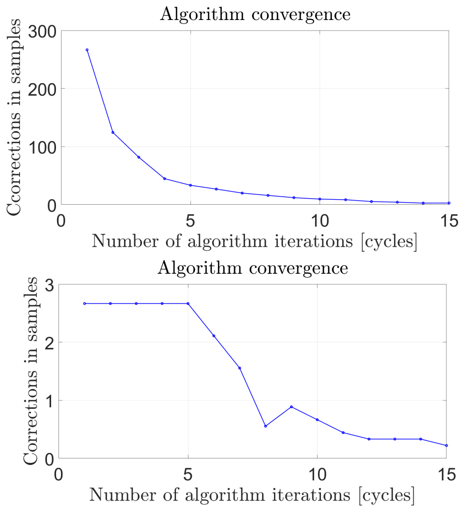

Figure 2: Algorithm convergence.

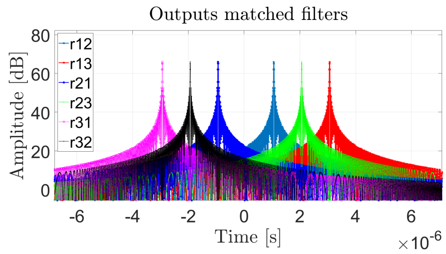

Figure 3: Iteration 1

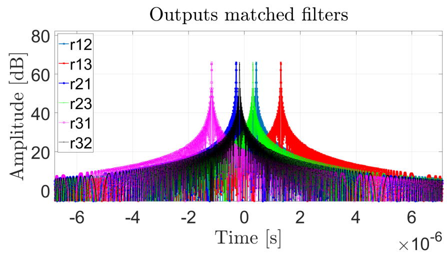

Figure 4: Iteration 3

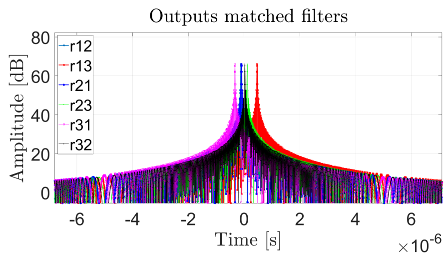

Figure 5: Iteration 6

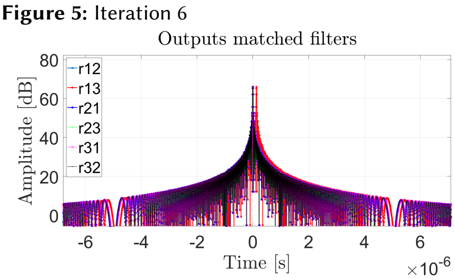

Figure 6: Iteration 8

After a period of synchronization, the primary and secondary nodes have the same clock time. In this work, we used a carrier wave of 1 GHz modulated with a 1.5 MHz sinusoidal wave.
After clock synchronization, the next step is to synchronize the phases of the waveforms. This is important because in relation to the distance from the primary sensor, all nodes must create a beam with constructive interference on the target. The formula used to adjust the phase contribution is [15]:

$$\phi_{adj}(\theta) = 2\pi \frac{d}{\lambda_{RF}}[1 - \sin(\theta)]$$

The simulated system is composed by 2 nodes, a block that simulates an instantaneous phase noise, and the phase shift blocks, which are controlled by a high precision ranging system [18]. In fig.7 the PLL structure is shown while the complete system is shown in fig.8.

3.2. Simulation results

In the final step, we assessed the nodes' performance by comparing the outputs of the phase shifters with the inputs. In Fig.9 and 10 we note that the system converges across all distances tested and remains resistant to small phase disturbances.

4. Conclusions

In this work, two different methods have been analyzed; after the implementation study and the simulation results we are able to determinate the advantages and disadvantages for both paths taken. The "TWTT Based ISL Link Method" we have the opportunity to develop both software, to face any implementation challenges, and hardware, to speed up algorithm processing. This algorithm convergence is ensured mathematically, indeed, it is well-known that the arithmetic mean can influence a set of data, improving its precision as well. A problem could

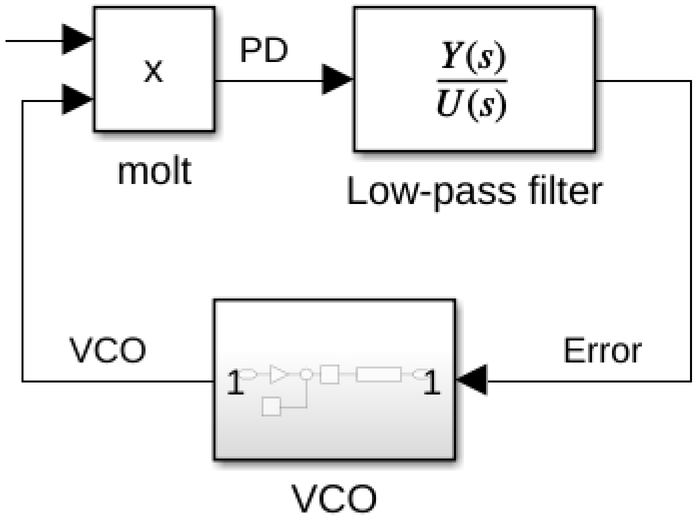

Figure 7: PLL block diagram.

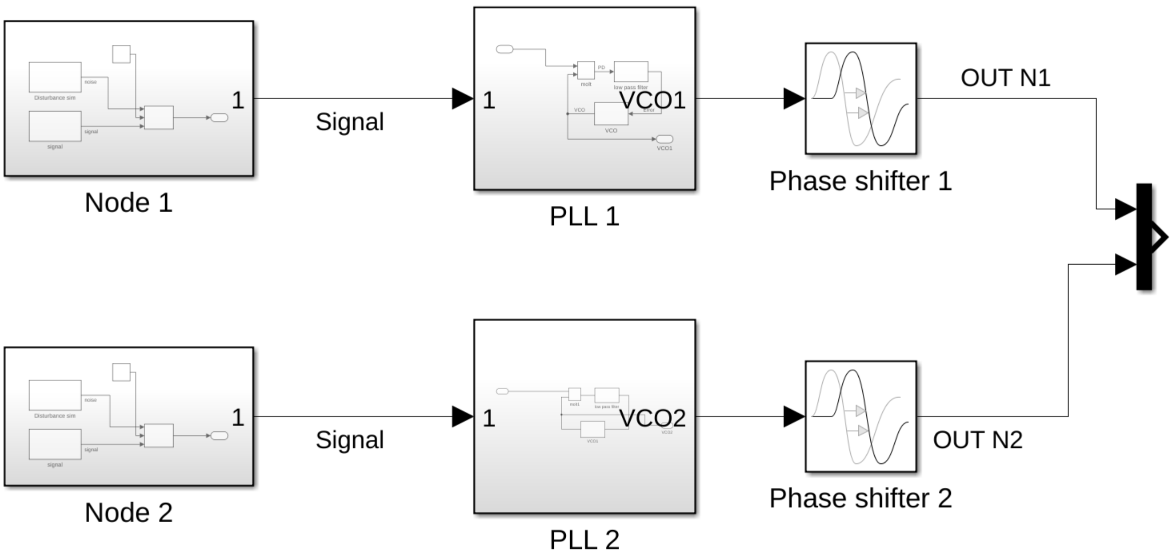

Figure 8: Complete system

be the rising of complexity in defining a communication protocol with increasingly large system. For the "PLL Based ISL Method" we are able to perform beamforming without DSP, which is an worth implementation semplification, but we need an high precision measurement system in X or W band which could be difficult in ISL systems.

In future works, new optimization methods based on neural approaches will be explored [20, 21, 22]

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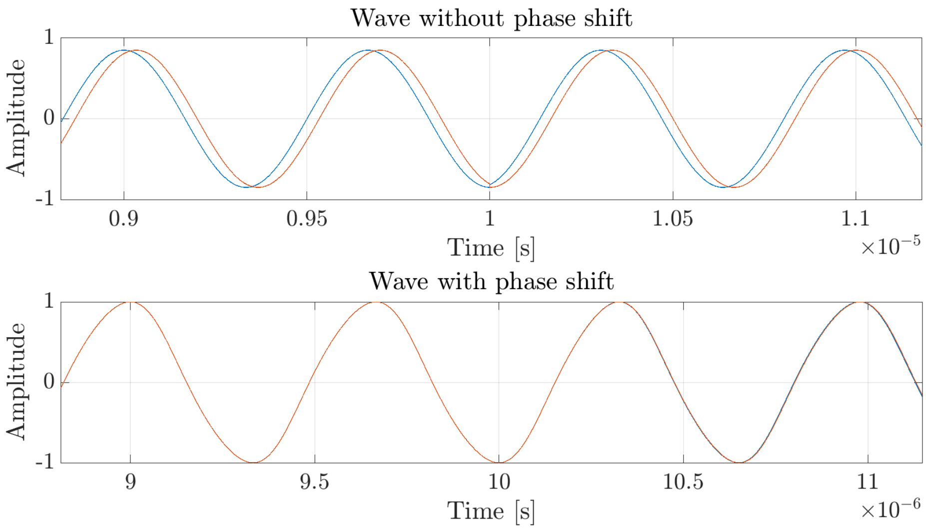

Figure 9: 40/50 m distance

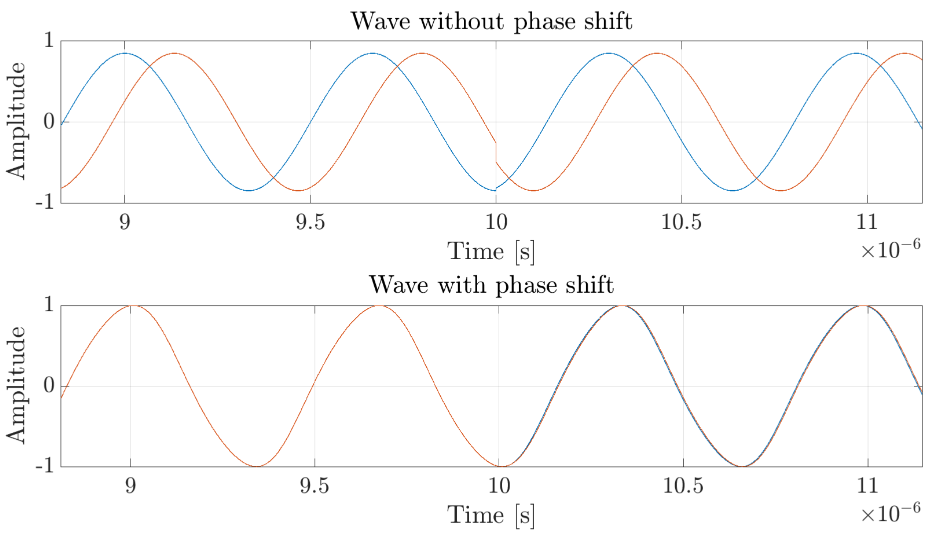

Figure 10: 10/50 m distance

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